AD-A221 975

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
9 May 1990

3. REPORT TYPE AND DATES COVERED
Final Report/1 Jan 87-31 Dec 89

4. TITLE AND SUBTITLE
Application of Solar Seigmology to Study
The Convection Zone

5. FUNDING NUMBERS
61102F/2311/A1

6. AUTHOR(S)
Dr Henry A Hill

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Arizona
Department of Physics
Tucson, AZ 85721

8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR.TR. 90-0553

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NP
Bolling AFB DC 20332-6448

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFOSR-87-0105

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Progress has been made in the program to use solar seismology as a tool for the understanding and potentially the forcasting of solar variability. Changes in the velocity of sound profile and nonadiabatic effects in the internal equilibrium condition of the convection zone over a six year period have been inferred from observed changes in the frequencies of low-order acoustic moses and intermediate degree f-modes. These changes may be associated with the eleven year solar cycle. The observed spectrum of gravity-modes has been used to infer a discontinuity in the mean molecular weight in the Sun's core and to place an upper limit on the density of WIMPS (Weakly Interacting Massive Particles) proposed to explain the solar neutrino paradox. The interred upper limit, if confirmed in future work, removes the WIMPS proposal as a viable option. Evidence for gravity-mode coupling has been extended from 4 multiplets to 20. This evidence for mode coupling leads to interesting predictions concerning the solar neutrino flux. New differential radius observations were obtained in 1988 and 1989.

14. SUBJECT TERMS
Sun; Solar Seigmology; Global Oscillations

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL SAR

AFOSR Contract No. AFOSR-87-0105

APPLICATION OF SOLAR SEISMOLOGY TO STUDY OF THE CONVECTION ZONE

Henry A. Hill, Principal Investigator
Department of Physics
University of Arizona
Tucson, Arizona 85721
(602) 621-6782

30 April 1990

Final Technical Report for January 1, 1987 to December 31, 1989

Prepared for

THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Ms. Kathleen L. Wetherell, Contracting Officer
Dr. Henry R. Radoski, Program Manager
AFOSR/NR
Bolling Air Force Base
Washington, DC 20332-6448

TABLE OF CONTENTS

Summary

Progress has been made in the program to use solar seismology as a tool for the understanding and potentially the forecasting of solar variability. Changes in the velocity of sound profile and nonadiabatic effects in the internal equilibrium condition of the convection zone over a six year period have been inferred from observed changes in the frequencies of low-order acoustic modes and intermediate degree f-modes. These changes may be associated with the eleven year solar cycle. The observed spectrum of gravity-modes has been used to infer a discontinuity in the mean molecular weight in the Sun's core and to place an upper limit on the density of WIMPS (Weakly Interacting Massive Particles) proposed to explain the solar neutrino paradox. The inferred upper limit, if confirmed in future work, removes the WIMPS proposal as a viable option. Evidence for gravity-mode coupling has been extended from 4 multiplets to 20. This evidence for mode coupling leads to interesting predictions concerning the solar neutrino paradox and temporal variations in the solar neutrino flux. New differential radius observations were obtained in 1988 and 1989.

1. Research Progress From 1 January 1988 to 31 December 1989 Under Contract No. AFOSR-87-0105

The research objective is to study solar variability through observation of certain types of variability and to examine properties of the solar convection zone relevant to understanding the driving mechanisms of active regions. The ability to anticipate certain types of variability will likely depend on an understanding of these mechanisms.

The observational approach is two-fold: (1) direct observation of certain types of solar variability -- changes in the solar diameter, solar oblateness, and limb-darkening function -- that are accessible through solar diameter observations, and (2) the study of the solar convection zone with solar seismology. In regards to the latter, the discovery of global oscillations of the Sun has made it possible to study the spatial and temporal behavior of the equilibrium conditions of the convection zone.

The research has been involved with the development of techniques for making observations, data reduction and data interpretation and the acquisition of data that will permit the study of the eigenfrequency spectrum of the Sun.

Work was conducted at SCLERA* on the analysis of total solar irradiance observations. An objective has been to better understand the properties of gravity mode signals in total irradiance. It was found that a significant fraction of the gravity mode power in total irradiance observations appears in sidebands of the classified gravity mode frequencies. These sidebands appear to be harmonics of the rotational frequencies of the nonuniform solar surface. This discovery will probably be quite valuable in addressing such questions as: (1) Why are total irradiance gravity mode signals so small relative to those obtained in differential radius observations at SCLERA? and (2) Why do various groups report highly discrepant results for the internal rotation rate of the Sun? These findings were presented at the XXVII Plenary COSPAR Meeting, July 18-29, 1988 in Helsinki, Finland (Kroll, Hill and Chen 1988).

A second paper that appeared in the COSPAR proceedings contains the most recent SCLERA results on changes over a six-year period in the low-order, low-degree acoustic and f-mode spectrum of the Sun (Oglesby, Hill and Rabaey 1988). These particular sets of modes are most sensitive to the Sun's convection zone and therefore, the observed changes in frequencies of oscillation are very likely due to changes in the convection zone.

---

* SCLERA is an acronym for the Santa Catalina Laboratory for Experimental Relativity by Astrometry, a research and educational program operating from both the Solar Studies Division and the Department of Physics in the Faculty of Science at the University of Arizona.

Temporal shifts of the referenced low-order, low-degree p-mode and intermediate-degree f-mode eigenfrequencies motivated a sensitivity analysis of the eigenfrequencies in preparation for a formal inversion (Rosenwald, Hill and Czarnowski 1988). The most interesting result from this analysis is that the frequencies for the f-modes possess a relatively high sensitivity to the entropy eigenfunction δs in the convection zone in comparison to that for the low-order acoustic modes. Estimates of implied changes in the internal structure of the Sun have been obtained using the results of the sensitivity analysis. It was inferred that $\Delta c/c \sim 0.01\%$ in the upper half of the convection zone, where c is the sound speed (Oglesby and Hill 1988).

The work on the extension of the range of gravity-mode classification was submitted for publication in 1988 and has been published (Hill and Gu 1990). The results reported in this paper were successfully tested by using the SCLERA 1978 diameter observations (Hill 1988), the SCLERA 1983 differential radius observations (Yi and Hill 1988), and the 1986-87 differential radius observations (Cornuelle and Hill 1989). The classifications were also tested in a fourth independent analysis. It has been predicted by Provost and Berthomieu (1988), that the distribution of observed amplitudes of the temperature eigenfunction of low-degree gravity modes should exhibit a minimum for eigenfrequencies corresponding to frequencies of divergence-free f-mode like oscillations at the surface. The amplitudes of the gravity modes classified by Hill and Gu (1990) were examined for minima at the predicted frequencies. The plot of power density versus frequency for the $\ell = 3$ modes has a well-defined minimum at $\nu \approx 148$ μHz while the plots for $\ell = 2$ and 4 modes have changes in slopes at $\nu \approx 115$ μHz and ≈ 180 μHz, respectively (cf. Hill et al. 1988). The presence of these 3 observationally obtained frequency features near the theoretically predicted locations of Provost and Berthomieu give support to the interpretation that the observed signals are due to oscillations in the solar atmosphere and that the ℓ classifications of the signals are also correct.

The asymptotic properties of the low-degree gravity modes classified by Hill and Gu (1990) were studied in the framework of asymptotic theory predictions (Gu, Hill and Rosenwald 1990). One of the more interesting findings of this analysis places a significant upper limit on the particle density of WIMPS which have been proposed to explain the solar neutrino paradox. The inferred upper limit, if confirmed, removes the WIMPS proposal as a viable option in solving the solar neutrino paradox.

The study by Gu, Hill and Rosenwald (1988) of the asymptotic properties of the gravity mode spectrum also found a fine structure between asymptotic theory eigenfrequencies and the observed eigenfrequencies reported by Hill and Gu (1990). This fine structure has been interpreted as the result of conditions not being met for the applicability of asymptotic theory at one or more radii in the solar interior. From an inversion of the observed fine structure by Hill, Gao and Rosenwald (1988), reasonably good agreement is obtained between observation and theory for a localized perturbation in internal structure at $r/R \approx 0.23$. The amplitude of the decrease in the mean molecular weight at $r/R \approx 0.23$ required to produce the fine structure has been inferred to be -0.9%. Such a localized decrease in the mean molecular weight could be caused by a partial mixing of the Sun's core in the past.

Intermediate-degree g-modes (those with angular order $\ell \approx 30$) were first observed in the late 1970's by Hill and Caudell (1979). However, it wasn't until 1986 that a preliminary survey was made of the 1979 differential radius observations (see Bos 1982) and a set of 4 multiplets exhibiting mode-locking were classified by Hill (1986). These multiplets with angular order $\ell \approx 30$ and eigenfrequencies of ≈ 350 µHz were used as a starting point for the comprehensive analysis discussed in this work. This comprehensive study culminated in the classification of a set of 20 intermediate-degree g-mode multiplets containing over 600 normal modes of oscillation (Rabaey and Hill 1989, 1990; Rabaey 1989a,b). Each of these multiplets was found to contain mode coupled sections. Of more importance however, is the internal properties of the Sun that can be inferred from this large body of classified modes. In this work we discuss two significant consequences.

Because these modes of oscillation are localized within the inner 50% of the Sun by radius and because of their large temperature eigenfunctions implied by the observed mode-locking, these modes of oscillation provide a modification of the effective temperature profile defined for a given process in the Sun. One of these processes is the ^{8}B neutrino production. The second consequence of these observations is a predicted periodic modulation of the neutrino production rates. The existence of a large set of mode-coupled gravity modes will lead to a low-frequency modulation of neutrino production rates which may account for the observed periodicity in the ^{8}B neutrino production (see Haubold and Gerth 1985). The prediction of this periodicity in the neutrino production rates is unique among all the competing theories that resolve the Solar neutrino paradox and is testable by the new generation of Solar neutrino detectors.

Theoretical work was completed which explored some of the nonlinear properties of gravity-mode oscillations in the solar interior (Czarnowski 1989). This work in particular was concerned with the interactions amongst the nonradial modes of a single rotationally split multiplet. Motivation for this analysis arose both from general theoretical interest and from observations of solar g-mode oscillations, which show strong evidence of nonlinear effects (Rabaey and Hill 1989, 1990; Rabaey 1989a,b). This work provides a general theoretical framework for investigating many problems of second- and third-order mode coupling in stellar systems. A multiple-scale perturbation technique was used. The formalism presents an alternative to that of Dziembowski (1982) and is more generally applicable.

The theory provides a means to infer the core amplitudes of the g-modes exhibiting the nonlinear behavior found by Rabaey and Hill (1989,1990) and Rabaey (1989,1990). These modes have radial order ≈ 15, angular degree ≈ 30. This is a significant accomplishment because it bypasses the traditional extrapolation of measured surface amplitudes into the interior, which is a questionable procedure, in part because of the uncertainty regarding the surface boundary conditions in the Sun. It was found that the relative radial displacement of these oscillations, $\delta r/r$, has a typical maximum amplitude in the interior of (6×10^{-4}). As a byproduct of the analysis, certain characteristics of the data used in conjunction with the theory allow the possibility of determining the linear damping time of these modes. Very preliminary results seem to indicate a typical damping time of about 40 years.

Two new analysis methods for solar seismology have been developed. Their use enables both the solar oscillation frequencies and the frequency dependencies on solar internal structure to be computed more accurately and efficiently than with existing methods. These two methods are called the continuous orthonormalization and adjoint sensitivity methods. There will be many valuable applications of these two methods in other fields of science as well as in astrophysics. This work was reported at the 172nd Meeting of the American Astronomical Society held in Kansas City, MO, June 5-8, 1988 (Rosenwald 1988), and an extensive analysis appears in the dissertation of Rosenwald (1989).

With the new analysis methods and the relatively large number of gravity modes classified at SCLERA, the foundation has been laid for a very effective program to further extend the domain of classified gravity modes.

References

Bos, R. J., 1982, Ph. D. Dissertation, University of Arizona.

Cornuelle, C. S. and Hill, H. A., 1990, "Evidence of Solar Gravity-Mode Oscillations in 1986-87 SCLERA Data," presented at the 175th meeting of the AAS, Washington, DC, Jan. 9-13.

Czarnowski, W. M., 1989, "Nonlinear Multi-mode Coupling of the Solar Gravity Modes in a Rotationally Split Multiplet," 174th meeting of the AAS, Ann Arbor, MI, June 11-15; abstract in Bulletin of the American Astronomical Society **21**, No. 2, 752.

Dziembowski, 1982, Acta Astron. **32**, 147.

Gu, Y., Hill, H. A. and Rosenwald, R. D., 1988, "Observed Asymptotic Properties of Low-Degree Solar Gravity Mode Eigenfrequencies," in Proc. Symp. Seismology of the Sun and Sun-like Stars, Tenerife, Spain, September 26-30, 1988. ESA SP-286, pp. 399-401.

Haubold, H. J. and Gerth, E., 1985, Aston. Nachr. **306**, 203.

Hill, H. A., 1986, "Evidence of Gravity-Mode Coupling and its Relevance to Solar Neutrino Production Rates", published in Neutrino '86: The 12th International Conference on Neutrino Physics and Astrophysics, Sendai, Japan, June 3-8, 1986, T. Kitagaki and H. Yuta, eds. (Kim Hup Lee Publishers, Singapore), 221-230.

Hill, H. A., 1988, "Tests of Solar Gravity Mode Classifications", Ap. J. Supplement, accepted for publication.

Hill, H. A. and Caudell, 1979, T. P., M.N.R.A.S. **186**, 327.

Hill, H. A. and Gu, Y, 1990, "Extension of the Range in Radial Order in the Detection and Mode Classification of Solar Low-Degree Gravity Modes," Scientia Sinica A **33**, No. 4, 67-79.

Hill, H. A., Fröhlich, C., Gabriel, M., and Kotev, V. A., 1990, "Solar Gravity Modes," in The Solar Interior and Atmosphere, eds. A. N. Cox, W. C. Livingston, and M. S. Matthews (University of Arizona Press), Chap. 14.

Hill, H. A., Gao, Q. and Rosenwald, R. D., 1988, "Inversion of Quasi-Periodic Deviations Between Low-Degree Solar Gravity Mode Eigenfrequencies and Asymptotic Theory Eigenfrequencies", in Proc. Symp. Seismology of the Sun and Sun-like Stars, Tenerife, Spain, September 26-30, 1988. ESA SP-286, pp. 403-406.

Kroll, R. J., Hill, H. A. and Chen, J., 1988, "Tests for the Properties of Solar Gravity Mode Signals in Total Irradiance Observations," COSPAR XXVII Plenary Meeting, Helsinki, Finland, July 18-29; Adv. Space Res. **8**, No. 7, (7)39-(7)42.

Oglesby, P. H. and Hill, H. A., 1988, "Temporal Changes in the Internal Structure of the Sun Inferred From Shifts in Eigenfrequency of the Low-Degree p_1-Modes and Intermediate-Degree f-Modes", 173rd Meeting of the American Astronomical Society, Boston, MA, January 8-12, 1989; abstract in Bulletin American Astronomical Society 20, No. 4, 1011.

Oglesby, P. H., Hill, H. A. and Rabaey, G. F., 1988, "Evidence for Temporal Variations in the Acoustic and f-Mode Eigenfrequency Spectrum of the Sun," COSPAR XXVII Plenary Meeting, Helsinki, Finland, July 18-29; Adv. Space Res. **8**, No. 7, (7)115-(7)118.

Provost, J. and Berthomieu, G., 1988, "Integrated Light and Velocity Variations of g-mode Oscillations", in Proceedings of the Symposium on Seismology of the Sun and Sun-like Stars, Tenerife, Spain; ESA SP-286, p. 387.

Rabaey, G. F., 1989a, "The Observed Properties of the Intermediate-Degree Gravity Modes and Their Relevance to the Solar Neutrino Paradox," presented at the 174th meeting of the AAS, Ann Arbor, MI, June 11-15, 1989; abstract in Bulletin of the American Astronomical Society **21**, No. 2, 752.

______________, 1989b, Ph.D. Dissertation, "Observed Properties of Intermediate-Degree g-Modes and Their Relevance to Solar Neutrino Paradox," University of Arizona.

Rabaey, G. F. and Hill, H. A., 1989, "The Intermediate-Degree g-mode Spectrum of the Sun: Its Properties and Their Implications to the Solar Neutrino Paradox," Fourteenth Texas Symposium on Relativistic Astrophysics, Dec. 11-16, Dallas, TX (1988); Annals NY Acad. Sci. **571**, 594-600.

____________________________, 1990, "The Observed Properties of the Intermediate-Degree Gravity Modes," accepted for publication in The Astrophysical Journal.

Rosenwald, R. D., 1988, "Continuous Orthonormalization and Adjoint Methods for Solar Seismology: Eigenfrequency Sensitivity Analysis", 172nd Meeting of the American Astronomical Society, Kansas City, MO, June 5-9, 1988; abstract in Bulletin of the American Astronomical Society **20**, 683.

Rosenwald, R. D., 1989, "The Development of the "Continuous Orthonormalization and Adjoint Methods for Solar Seismology: Eigenfrequency Computation and Sensitivity Analysis for Direct and Inverse Problems," Ph.D. Dissertation, University of Arizona.

Rosenwald, R. D., Hill, H. A. and Czarnowski, W. M., 1988, "Eigenfrequency Sensitivities of Solar p_1-Modes and f-Modes", 173rd Meeting of the American Astronomical Society, Boston, MA, January 8-12, 1989; abstract in Bulletin American Astronomical Society **20**, No. 4, 1011.

Yi, L. and Hill, H. A., 1988, "Evidence of Gravity Mode Signals in 1983 Differential Radius Observations of the Sun", 173rd Meeting of the American Astronomical Society, Boston, MA, January 8-12, 1989; abstract in Bulletin American Astronomical Society **20**, No. 4, 1011.

2. Publications*

Cornuelle, C. S. and Hill, H. A., 1990, "Evidence of Solar Gravity-Mode Oscillations in 1986-87 SCLERA Data," presented at the 175th meeting of the AAS, Washington, DC, Jan. 9-13.

Czarnowski, W. M., 1989, "Nonlinear Multi-mode Coupling of the Solar Gravity Modes in a Rotationally Split Multiplet," 174th meeting of the AAS, Ann Arbor, MI, June 11-15, 1989; abstract in Bulletin of the American Astronomical Society 21, No. 2, 752.

Gu, Y., Hill, H. A. and Rosenwald, R. D., 1988, "Observed Asymptotic Properties of Low-Degree Solar Gravity Mode Eigenfrequencies," in Proc. Symp. Seismology of the Sun and Sun-like Stars, Tenerife, Spain, September 26-30, 1988. ESA SP-286, pp. 399-401.

Hill, H. A., 1988, "Tests of the Detection and Mode Classification of Low-Degree Solar Gravity Modes with 1978 Solar Diameter Observations," Astrophysical Journal Supplement Series, accepted for publication.

Hill, H. A. and Gu, Y, 1990, "Extension of the Range in Radial Order in the Detection and Mode Classification of Solar Low-Degree Gravity Modes," Scientia Sinica A 33, No. 4, 67-79.

Hill, H. A., Cornuelle, C. S. and Germain, M. E., 1988, "Properties of Solar Gravity-Mode Eigenfunctions in the Photosphere," 173rd Meeting of the American Astronomical Society, Boston, MA, January 8-12, 1989; abstract in Bulletin of the American Astronomical Society 20, 1012.

Hill, H. A., Frohlich, C., Gabriel, M., and Kotev, V. A., 1990, "Solar Gravity Modes," in The Solar Interior and Atmosphere, eds. A. N. Cox, W. C. Livingston, and M. S. Matthews (University of Arizona Press), Chap. 14.

Hill, H. A., Gao, Q. and Rosenwald, R. D., 1988, "Inversion of Quasi-Periodic Deviations Between Low-Degree Solar Gravity Mode Eigenfrequencies and Asymptotic Theory Eigenfrequencies," in Proc. Symp. Seismology of the Sun and Sun-like Stars, Tenerife, Spain, September 26-30, 1988. ESA SP-286, pp. 403-406.

Hill, H. A., Huang, Y. and Kroll, R. J., 1988, "The Detection of Gravity Mode Signals in Differential Radius and Total Irradiance Observations" in Solar Radiative Output Variations: Proceedings of a Workshop, P. Foukal ed., 221-223.

Kroll, R. J., Chen, J. and Hill, H. A., 1988, "Properties of Solar Gravity Mode Signals in Total Irradiance Observations," in Proc. Symp. Seismology of the Sun and Sun-like Stars, Tenerife, Spain, September 26-30, 1988. ESA SP-286, pp. 415-418.

*Publications from work supported in part by the Air Force Office of Scientific Research.

Kroll, R. J., Hill, H. A. and Chen, J.. 1988, "Tests for the Properties of *Solar Gravity Mode Signals in Total Irradiance Observations*," Adv. Space Res. **8**, No. 7, (7)39-(7)42.

Oglesby, P. H. and Hill, H. A., 1988, "Temporal Changes in the Internal Structure of the Sun Inferred From Shifts in Eigenfrequency of the Low-Degree p_1-Modes and Intermediate-Degree f-Modes," 173rd Meeting of the American Astronomical Society, Boston, MA, January 8-12, 1989; abstract in Bulletin of the American Astronomical Society **20**, 1011.

Oglesby, P. H., Hill, H. A. and Rabaey, G. F., 1988, "Evidence for Temporal Variations in the Acoustic and f-Mode Eigenfrequency Spectrum of the Sun," Adv. Space Res. **8**, No. 7, (7)115-(7)118.

Rabaey, G. F., 1989, "The Observed Properties of the Intermediate-Degree Gravity Modes and their Relevance to the Solar Neutrino Paradox," presented at the 174th meeting of the AAS, Ann Arbor, MI, June 11-15, 1989; abstract in Bulletin of the American Astronomical Society **21**, No. 2, 752.

Rabaey, G. F. and Hill, H. A., 1989, "The Intermediate-Degree g-mode Spectrum of the Sun: Its Properties and Their Implications to the Solar Neutrino Paradox," Fourteenth Texas Symposium on Relativistic Astrophysics, Dec. 11-16, Dallas, TX (1988); Annals NY Acad. Sci. **571**, 594-600.

Rabaey, G. F., Hill, H. A. and Barry, C. T., 1988, "The Observed Intermediate-Degree f-Mode Eigenfrequency *Spectrum of the Sun and* Tests of the Mode Classification Proficiency," Astrophysics and Space Science **143**, 81-97 (1988).

Rosenwald, R. D., 1988, "Continuous Orthonormalization and Adjoint Methods for Solar Seismology: Eigenfrequency Sensitivity Analysis," 172nd meeting of the AAS, Kansas City, MO, June 5-9; abstract in Bulletin of the American Astronomical Society **20**, 683.

Rosenwald, R. D., Hill, H. A. and Czarnowski, W. M., 1988, "Eigenfrequency Sensitivities of Solar p_1-Modes and f-Modes," 173rd Meeting of the American Astronomical Society, Boston, MA, January 8-12, 1989; abstract in Bulletin of the American Astronomical Society **20**, 1011.

Yi, L. and Hill, H. A., 1988, "Evidence of Gravity Mode Signals in 1983 Differential Radius Observations of the Sun," 173rd Meeting of the American Astronomical Society, Boston, MA, January 8-12, 1989; abstract in Bulletin of the American Astronomical Society **20**, 1011.

3. Advanced Degrees Awarded

William M. Czarnowski, 1989 Ph.D. Dissertation, "Nonlinear Multimode Coupling of the Solar g-Modes: A Rotationally Split Multiplet."

Gregory F. Rabaey, 1989 Ph.D. Dissertation, "Observed Properties of Intermediate-Degree g-Modes and Their Relevance to Solar Neutrino Paradox."

Ross D. Rosenwald, 1989 Ph.D. Dissertation, "The Development of the "Continuous Orthonormalization and Adjoint Methods for Solar Seismology: Eigenfrequency Computation and Sensitivity Analysis for Direct and Inverse Problems."

4. 1988 and 1989 Talks Presented at Conferences and Seminars

February 18-20, 1988	Drs. Hill and Oglesby attended the Ninth Annual Fairborn-Smithsonian IAPPP Symposium held in Tucson, AZ. Contributed paper, "New Solar Seismograph for Use in a Global Network."
March 7, 1988	Dr. Hill gave a colloquium at the Department of Astronomy, University of Arizona.
April 29, 1988	Dr. Hill gave a colloquium at the Department of Atmospheric Sciences, University of Arizona.
June 5-9, 1988	Dr. Burt Beardsley and Mr. Ross Rosenwald attended the 172nd Meeting of the American Astronomical Society held in Kansas City, MO. Beardsley presented a poster paper and Rosenwald gave a talk on his dissertation work, "Continuous Orthonormalization and Adjoint Methods for Solar Seismology: Eigenfrequency Sensitivity Analysis."
July 11-17, 1988	Dr. Hill was a guest of the USSR Academy of Sciences.
July 13, 1988	Dr. Hill gave a lecture at the Sternberg Institute, Moscow State University, Moscow.
July 15, 1988	Dr. Hill gave a lecture at the Institute for Nuclear Research, USSR Academy of Sciences.
July 18-29, 1988	Two papers were presented at COSPAR (Committee on Space Research): one by H. A. Hill & R. J. Kroll and another by P. H. Oglesby, H. A. Hill & G. F. Rabaey.
Sept. 22, 1988	Dr. Hill gave a seminar at NASA Goddard Space Center, Greenbelt, MD
Nov. 15-18, 1988	Dr. Hill and Gregory Rabaey attended the conference on The Solar Interior and Atmosphere," held in Tucson, AZ. Dr. Hill gave an oral presentation.
Dec. 11-16, 1988	Dr. Hill and Gregory Rabaey attended the Fourteenth Texas Symposium on Relativistic Astrophysics," in Dallas, TX. Mr. Rabaey gave an oral presentation.
June 11-15, 1989	Dr. Bill Czarnowski presented a paper, "Nonlinear Multi-mode Coupling of the Solar Gravity Modes in a Rotationally Split Multiplet," at the 174th Meeting of the AAS, Ann Arbor, MI.
June 1989	Dr. Hill gave a colloquium at IZMIRAN and Moscow State University in Moscow, USSR.
December 1989	Dr. Hill gave colloquia at Yunnan Observatory, Kunming, PRC.